NISTIR 6588

# FIFTEENTH MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY MARCH 1-7, 2000

## VOLUME 2

Sheilda L. Bryner, Editor

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**U. S. Department of Commerce**
Norman Y. Mineta, Secretary
**Technology Administration**
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**National Institute of Standards and Technology**
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# A PRELIMINARY MODEL FOR URBAN FIRE SPREAD

## - Building Fire Behavior Under the Influence of External Heat and Wind -

by
Keisuke HIMOTO and Takeyoshi TANAKA
DPRI, Kyoto University
Gokasho, Uji, Kyoto 611-0011, JAPAN

## 1. INTRODUCTION

Post-earthquake fires are considered to be one of the important factors that enlarge the damage when a densely inhabited urban area is hit by a severe earthquake. It will be necessary to have a means for predicting the behavior of urban fires in order to explore the measures to effectively mitigate the damage caused by such post-earthquake fires.

Several models are already available in Japan for the purpose of predicting the fire spread in urban areas. It can be said that these models were developed based on the model so-called "Hamada formula", which was introduced by Hamada, Emeritus of University of Tokyo more than 50 years ago[1]. The Hamada model was constructed mainly based on the statistical data on the spread of the urban fires in the past, which frequently burned Japanese cities into ashes, as a function of wind velocity. However, now that the conditions of the cites, including building materials and constructions, have extremely changed, it is doubtful that the validity of the statistically-based model still remains.

It is considered to be necessary to develop a physically-based model for the better assessment of the post-earthquake fire loss in modern cities. In this study, a model for predicting fire spread from a building to another was explored in a simple configuration as the first step. The ultimate goal of this study is to construct a model which is capable of predicting the fire spread in the cities in which a number of houses are arbitrarily located.

## 2. THE URBAN FIRE SPREAD MODEL

### 2-1.Concept of the Model

A city consists of buildings having different conditions and being arrayed in a complex geometrical relationship. The behavior of an urban fire will be affected by such man-made conditions as well as weather conditions such as general wind velocity. Here, it is regarded that an urban fire is the cluster of burnings of many individual buildings simultaneously involved in the fire. In other words, predicting an urban fire is nothing but predicting each of these buildings involved. A significant difference of this prediction from conventional predictions of building fires is that a building is ignited and burns under the thermal environment induced by the fires of the other buildings.

The urban fire model considered in this study consists of two parts as follows:

*(a) Prediction of individual building fire:*

The model is, as illustrated in FIGURE 1, similar to one of the conventional one layer compartment fire models to a certain degree[2][3]. The predictions of the heat transfer to the boundary, the vent flow, the heat conduction in walls containing moisture and the mass burning rate as a function of the room temperature are incorporated. The compartment gases are assumed to be black from the beginning. This fire compartment exchange heat with the external environment at elevated temperature and radiation source. The heat ejects from the fire to the outside of the building, which constitutes the heat with source of temperature environment, is also an indispensable output of the prediction.

*(b )Thermal environment of the building:*

It is assumed that a building is exposed to the elevated temperature due to wind blown plumes as well as the thermal radiation from other buildings on fire as illustrated in FIGURE 2. Although fire brands are another important mechanism of fire spread, this is not taken into account in the model at this moment.

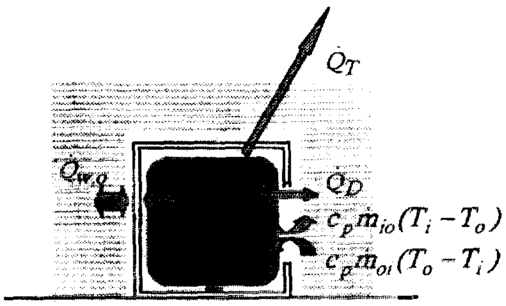


FIGURE 1. Heat transfer between gases inside the building and the atmosphere

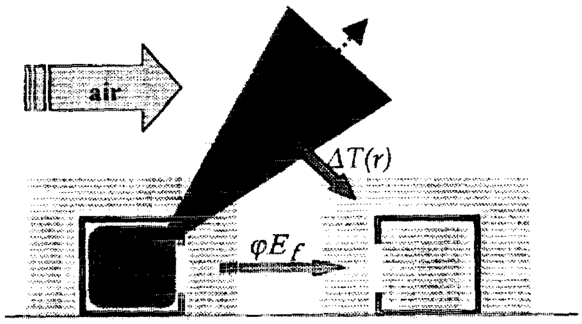


FIGURE 2. Heat transfer between different buildings

## 2-2. Modeling of the Building Fire

Basically just like one of the existing compartment fire models, the part of the building fire can be formulated as follows:

### 2-2-1. Zone relationship

In this model, the relationships which hold for physical properties in the compartment gases, considered as a zone, are described as follows:

**(1) Conservation of mass**

$$\frac{d}{dt}(\rho_i V_i) = \sum \dot{m}_{oi} - \sum \dot{m}_{io} + \dot{m}_{b,i} \tag{1}$$

**(2) Conservation of energy**

$$\frac{d}{dt}(c_p \rho_i T_i V_i) = \dot{Q}_{c,i} - \sum \dot{Q}_{W,i} - \sum \dot{Q}_D + \sum c_p \dot{m}_{oi} T_o - \sum c_p \dot{m}_{io} T_i - (qL_f - c_p T_f)\dot{m}_{b,i} \tag{2}$$

**(3) Conservation of oxygen**

$$\frac{d}{dt}(\rho_i V_i Y_{O2,i}) = \sum \dot{m}_{oi} Y_{O2,o} - \sum \dot{m}_{io} Y_{O2,i} - \Gamma_{O2,i} \tag{3}$$

**(4) Conservation of combustible gases**

$$\frac{d}{dt}(\rho_i V_i Y_{f,i}) = \sum \dot{m}_{oi} Y_{f,o} - \sum \dot{m}_{io} Y_{f,i} + \dot{m}_{b,i} - \Gamma_{f,i} \tag{4}$$

**(5) Equation of gas state**

$$\rho_i T_i = \rho_o T_o \tag{5}$$

Eqns.(1)-(5) hold for an arbitrary space in a building having multiple spaces and openings, and $\sum$ devotes to take sum of the concerning walls or openings.

### 2-2-2. Zone Equations

From Eqns.(1) - (5), the following formulas, useful for computations of the model, can be derived:

**(1) Compartment gas temperature**

$$\frac{dT_i}{dt} = \frac{T_i}{c_p \rho_o T_o V_i}\left[\dot{Q}_{c,i} - \sum \dot{Q}_{W,i} - \sum \dot{Q}_D + c_p \sum \dot{m}_{oi}(T_o - T_i) + \left\{-qL_f + c_p(T_f - T_i)\right\}\dot{m}_{b,i}\right] \tag{6}$$

**(2) Concentration of oxygen**

$$\frac{dY_{O2,i}}{dt} = \frac{T_i}{\rho_o T_o V_i}\left\{\sum \dot{m}_{oi}\left(Y_{O2,o} - Y_{O2,i}\right) - \left(\Gamma_{O2,i} + \dot{m}_{b,i} Y_{O2,i}\right)\right\} \tag{7}$$

**(3) Concentration of combustible gas**

$$\frac{dY_{f,i}}{dt} = \frac{T_i}{\rho_o T_o V_i}\left\{\sum \dot{m}_{oi}\left(Y_{f,o} - Y_{f,i}\right) + \dot{m}_{b,i}\left(1 - Y_{f,i}\right) - \Gamma_{f,i}\right\} \tag{8}$$

**(4) Pressure equation**

$$\frac{\dot{Q}_{c,i} - \sum \dot{Q}_{W,i} - \sum \dot{Q}_D}{c_p \rho_o T_o \sqrt{g} \sum \left(A\sqrt{H}\right)} + \frac{\sum \dot{m}_{oi} T_o - \sum \dot{m}_{io} T_i}{\rho_o T_o \sqrt{g} \sum \left(A\sqrt{H}\right)} - \frac{\left(qL_f - c_p T_f\right)\dot{m}_{b,i}}{c_p \rho_o T_o \sqrt{g} \sum \left(A\sqrt{H}\right)} = 0 \tag{9}$$

### 2-2-3. Modeling of elements

Eqns. (6) - (9) are supplemented with the component processes such as burning rates, heat release rate, openings flow rate, etc. as follows to form a closed system of the equations to actually solve this model.

**(1) Mass burning rate**

It is considered that the fuels to feed the compartment fire consist of live fire load and built-in combustible such as interior lining and timber structural members. It is assumed here that the mass burning rates of the two kinds of fire loads are given as

$$\dot{m}_{b,i} = \frac{1}{4}\frac{\sigma\left(T_i^4 - T_f^4\right) + h_{fuel}\left(T_i - T_f\right)}{qL_f} A_{fuel} \tag{10}$$

where the coefficient 1/4 is the empirical constant from the experiments by Ohmiya et. al to take into account the insulation effect of char layer on the surface of combustibles [4].

In case of the live fire load, the surface area of the fuel $A_{fuel}$ is estimated by following

$$A_{fuel} = \phi w A_{floor} \tag{11}$$

where $\phi$ is the fuel surface area coefficient first introduced by Harmathy [5]. According to the live load survey by Aburano et. al survey of actual combustibles, $\phi$ is correlated with live fire load density $w$ as [6]

$$\phi = 0.61 w^{-2/3} \tag{12}$$

**(2) Heat generation rate**

Obviously, the heat release rate within the compartment is supposed to be controlled whichever the smaller of the heat releases due to the supply rates of the fuel and oxygen. Hence,

$$\dot{Q}_{c,i} = \min\left\{\Delta H_f\left(\dot{m}_{b,i} + \sum \dot{m}_{oi} Y_{f,o}\right), \Delta H_{O2} \sum \dot{m}_{oi} Y_{O2,o}\right\} \tag{13}$$

**(3)Consumption rate of chemical species**

Using the heat generation rate is determined like (13), the consumption rates of oxygen and combustible fuel are respectively given by

$$\Gamma_{O2,i} = \frac{\dot{Q}_{c,i}}{\Delta H_{O2}} \tag{14}$$

$$\Gamma_{f,i} = \frac{Q_{c,i}}{\Delta H_f} \tag{15}$$

**(4)Heat loss to the wall**

The heat losses to inside and outside of the compartment wall surfaces, in other words the negative heat gain of the wall are respectively calculated as follows:

$$\dot{Q}_{W,i} = \dot{q}_0'' A_W = \left\{\varepsilon_{W,i}\sigma\left(T_i^4 - T_{W,i}^4\right) + h_i\left(T_i - T_{W,i}\right)\right\} A_W \tag{16}$$

$$Q_{W,o} = \dot{q}_l'' A_W = \left\{\varepsilon_{W,o}(1-\varphi_w)\sigma T_o^4 - \varepsilon_{W,o}\sigma T_{W,o}^4 + h_o\left(T_o - T_{W,o}\right) + \varphi_w E_f\right\} A_W \tag{17}$$

The surface temperature of the compartment wall in Eqn.(16) and (17), $T_{w,i}$ and $T_{w,o}$ , can be obtained numerically solving the one dimensional heat conduction equation with moisture content as

$$\frac{\partial T}{\partial t} = \left(\frac{k}{c\rho}\right)\frac{\partial^2 T}{\partial t^2} - \frac{\dot{q}_v}{c\rho} \tag{18}$$

with the boundary conditions as

$$-k\frac{\partial T}{\partial x}\Big|_{x=0} = \dot{q}_0''(t) \tag{19-1}$$

$$-k\frac{\partial T}{\partial x}\Big|_{x=l} = -\dot{q}_l''(t) \tag{19-2}$$

In this model, the evaporation of water begins at the boiling point and the temperature stays until all the water in the wall be evaporated.

**(5) Heat loss from the opening by radiation**

The compartment receives radiation from the external sources, i.e., houses on fire, through the opening, and in return emit heat back to the outside due to the elevation of the compartment temperature. The net radiation heat loss through the opening can be written as.

$$\dot{Q}_D = \left\{\sigma T_i^4 - (1-\varphi_d)\sigma T_o^4 - \varphi_d E_f\right\} A_D \tag{20}$$

Note that the net heat loss can be negative depending on the intensity of the external source and the compartment temperature.

**(6)Opening flow rate**

The rates of flows through the openings can be formulated as a function of the temperatures and the pressures of the compartment and the outdoor. And then the compartment pressure is solved to satisfy Eqn.(9).

**(7)Heat emission to outside of the compartment**

It is necessary to estimate the heat ejected out through the opening, because this turns into the driving force of the fire-induced hot air flow to which other buildings are exposed. The heat consists of the heat of combustion of excess fuel and the enthalpy of the opening flow at elevated temperature. Hence,

$$\dot{Q}_T = \left(\Delta H_f \dot{m}_{b,i} - \dot{Q}_{c,i}\right) + c_p \sum \dot{m}_{io}(T_i - T_o) \tag{21}$$

## 2-3.Modeling of External Conditions

As was already mentioned, it is indispensable for an urban fire spread model to take into account the external wind and the thermal environments of buildings, i.e. thermal radiation and atmospheric temperature elevation due to blown down fire plume induced by the burning of the other buildings. The issue of fire brands are not dealt with in this model although it should be incorporated in the future.

### 2-3-1. Wind pressure coefficient

Winds blow down the fire plumes from burning buildings and also enhance the ventilation of burning building, thereby affecting the behavior of the fires of the buildings. In order to assess the wind pressures on building surfaces, the angle between the direction of wind and a building surface, as illustrated in FIGURE 3, has to be known. Hence, a rectangular coordinate system (x, y, z) is considered on the urban terrain where x-axis and y-axis are set for east-west and north-south directions, respectively, and z-axis for vertical direction.

Although the distribution of the wind pressure coefficient $C_N$ acting on actual building surfaces are rather complicated, the coefficient is approximated in this model as follows:

$$C_N = \begin{cases} -0.8 + 0.3\cos\eta & (\cos\eta \geq 0) \\ -0.8 - 1.6\cos\eta & (\cos\eta < 0) \end{cases} \tag{22}$$

where $\cos\eta$ is the cosine of the angle between the directional vector $\mathbf{v} = (v_x, v_y)$ of the wind and the normal vector $\mathbf{n}$ of the surface, which can be given as $\cos\eta = (\mathbf{v}, \mathbf{n})$.

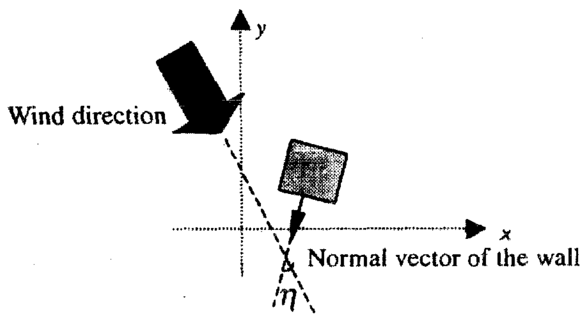


FIGURE 3. Wind direction and normal

### 2-3-2. Fire-induced plume

**(1) Temperature along wind blown plume axis**

Although the behaviors of usual vertical plumes have been well studied[7], there is not ample data on the fire plumes that are blown down by external winds. From what little existing wind tunnel experiment, it is not clear if the wind enhance or reduce the plume entrainment[8]. Here, the results from vertical plumes are used to assess the temperature in the down stream of a burning building, until new findings have been obtained on this topic, i.e. the temperature rise along the axis of the plume is given as:

$$\Delta T_0 = \begin{cases} 900 & (\frac{z}{\dot{Q}_T^{2/5}} < 0.08) \\ 60\left(\frac{z}{\dot{Q}_T^{2/5}}\right)^{-1} & (0.08 \le \frac{z}{\dot{Q}_T^{2/5}} \le 0.2) \\ 24\left(\frac{z}{\dot{Q}_T^{2/5}}\right)^{-5/3} & (0.2 < \frac{z}{\dot{Q}_T^{2/5}}) \end{cases} \tag{23}$$

**(2) Rise angle of a plume axis**

The results on rise angle of the axis of a plume blown down cannot be said ample either. Here we temporarily employ the result from the wind tunnel experiments for the line-heat source by Yokoi [8], which is given by

$$\tan\theta = 0.1\Omega^{-1/4} \tag{24}$$

where $\Omega$ is the non-dimensional parameter defined as

$$\Omega \equiv \frac{U_\infty}{\left(\frac{Q'g}{c_p\rho_o T_o}\right)^{1/3}} = \frac{U_\infty}{\left(\frac{\dot{Q}_T g}{c_p\rho_o T_o\sqrt{A_{floor}}}\right)^{1/3}} \tag{25}$$

**(3) Off axis temperature**

Buildings are located on the terrain surface, so usually more or less at a remote position from the plume axis. Letting $r$ be the distance to the point of interest, i.e., position of a building, the temperature rise at the point is calculated as (FIGURE 4) :

$$\Delta T(r) = \Delta T_0 exp\left\{-\left(\frac{r}{b}\right)^2\right\} \tag{26}$$

where the distance $r$ is calculated as (FIGURE 5) :

$$r = |G_0 - P_o| = \sqrt{|G_0|^2 - (G_0, a)^2} \tag{27}$$

with

$$a = \frac{(v_x, v_y, \tan\theta)}{1+\tan^2\theta} \tag{28}$$

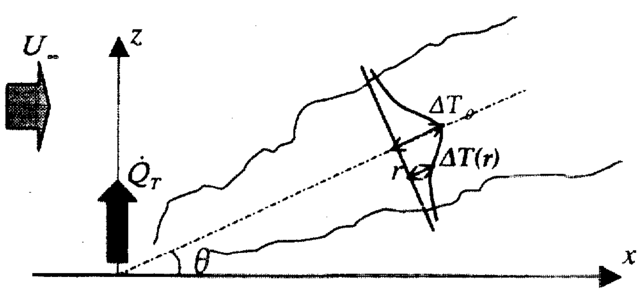


FIGURE 4. Plume axis and distance $r$

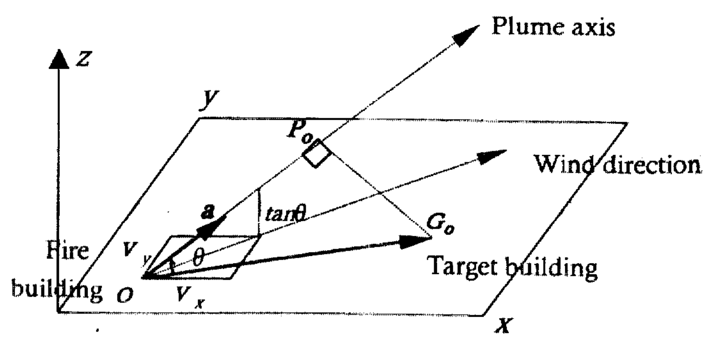


FIGURE 5. Plume axis and target building

### 2-3-3. Thermal radiation from building fire

A building receive the radiant heat from multiple surfaces of multiple buildings on fire, so the total radiant heat flux incident upon a target building is given as

$$\dot{q}''_R = \sum_{j=1}^{N}\left(E_j F_{ij}\right) \tag{29}$$

However, the actual calculation of the view factors included in Eqn.(29) is quite complicated in real city configuration so an attempt is now being made to develop a practical means of the calculation.

## 3. PRELIMINARY SAMPLE CALCULATIONS

Although the model has not been completed yet that the fire spread predictions in a actual urban configuration is not possible, some preliminary calculations in simple geometric conditions were carried out. The buildings of the same sizes are arrayed in parallel in a row so that the configuration factors involved can be calculated by a well-known formula as follows:

$$X = \frac{s}{u}, Y = \frac{t}{u}$$

$$F_{d1-2} = \frac{1}{2\pi}\left(\frac{X}{\sqrt{1+X^2}}\tan^{-1}\frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\frac{X}{\sqrt{1+Y^2}}\right) \tag{30}$$

### 3-1. Conditions in common

**(1) Building geometry**

Small-scale rectangular parallelepiped compartment of 4.0[m] by 4.0[m] square floor with 2.5[m] of height is considered in the calculation.

**(2) Opening size**

The opening with the dimensions of 2.0[m] by 2.0[m] is considered.

**(3) Wall property**

The wall is assumed to be normal-weight concrete having physical properties as follows as shown in TABLE 1. The thickness is uniformly 0.1[m] in all walls.

**(4) Fuel property**

The physical properties of wood are used as those of the fuel. The fire load density is 30.0[kg/m$^2$].

**(5) Weather condition**

The wind direction is made to be west wind and on the wind velocity, it is supposed to be made to change from windless 0.0[m/s], 4.0[m/s] and 8.0[m/s].

TABLE 1. Wall properties

| | Thermal conductivity [kW/m·K] | Density [kg/m$^3$] | Specific heat [kJ/kg·K] | Thickness [m] | Water content [kg/m$^3$] |
|---|---|---|---|---|---|
| Properties | 0.0163 | 2250 | 0.895 | 0.1 | 5.0 |

### 3-2. Calculation-A

A rectangular radiation source with 150[kW/m$^2$] of emissive power is assumed in front of the building as shown in FIGURE 6. The only opening of the building faces to the heat source. The air temperature to which the building exposed is specified at 500[K] in this case. This calculation is to exhibit how the building fire model behaves and the result is shown at FIGURE 7.

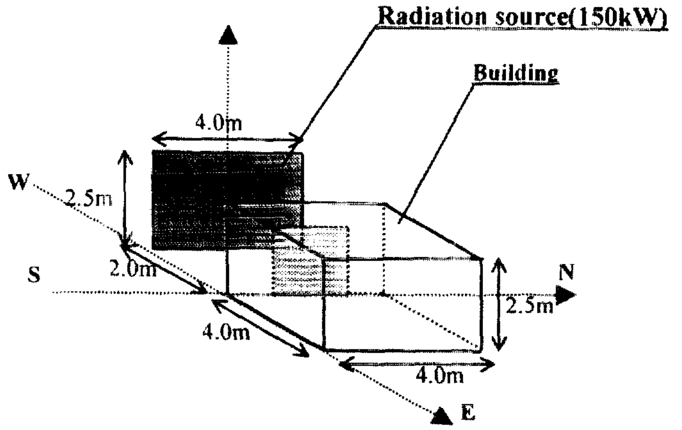


FIGURE 6. Calculation-A condition

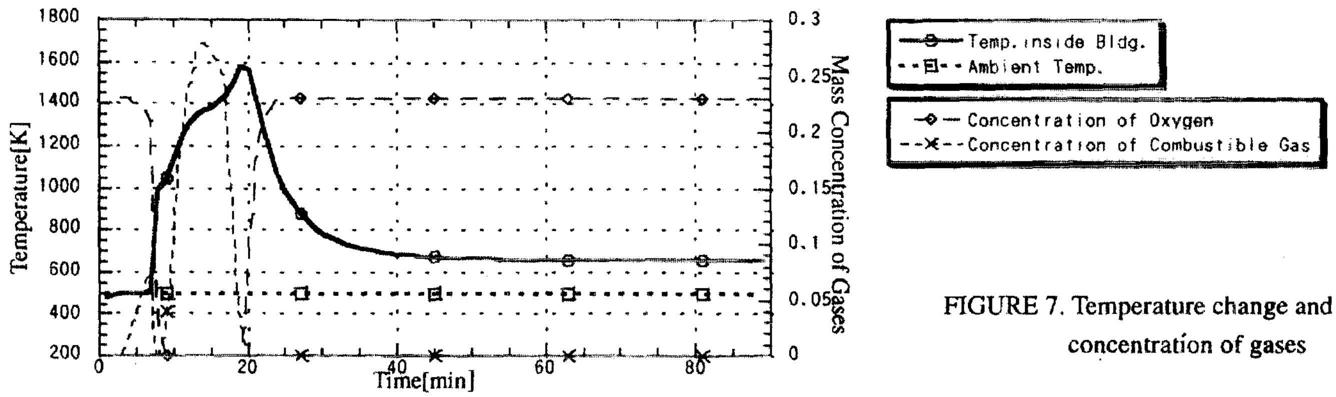


FIGURE 7. Temperature change and concentration of gases

The combustibles in the building was ignited by receiving heat from the outside and the temperature rises fairly quickly to around 1400[K], and the temperature started to go down due to the burnt out when 20[min] has passed. The reason why the temperature does not come down to the ambient temperature after the burnt out is attributed to the fact that the building is always exposed to the radiation.

### 3-3. Calculation-B

In this calculation, 3 buildings, which is mentioned earlier in condition (1), are placed in parallel in a row as shown in FIGURE 8. A fire is artificially initiated at the west end building. The calculations are carried out for the wind velocity from 0.0, 4.0 and 8.0[m/s]. This time, the opening of the first building is set on the east wall and the others in the west. The initial ambient temperature is 300.0[K].The results are shown at FIGURE 9-11.

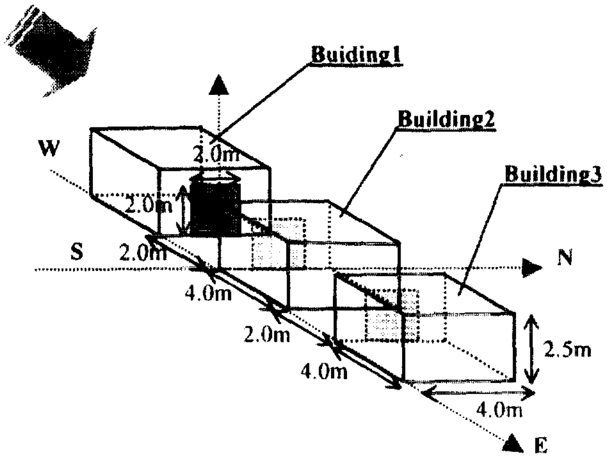


FIGURE 8. Calculation-B condition

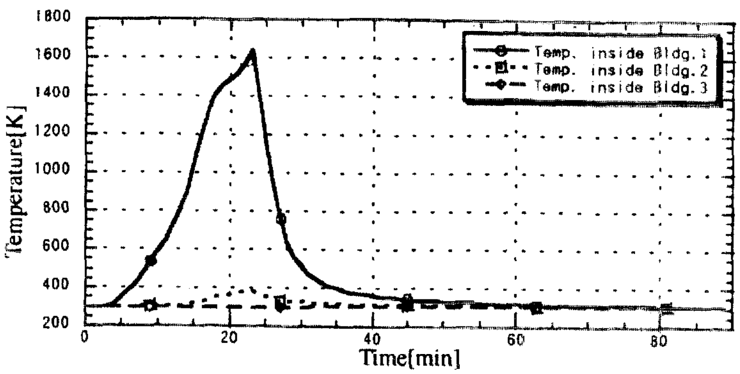


FIGURE 9. Temperature change-a (0.0m/s)

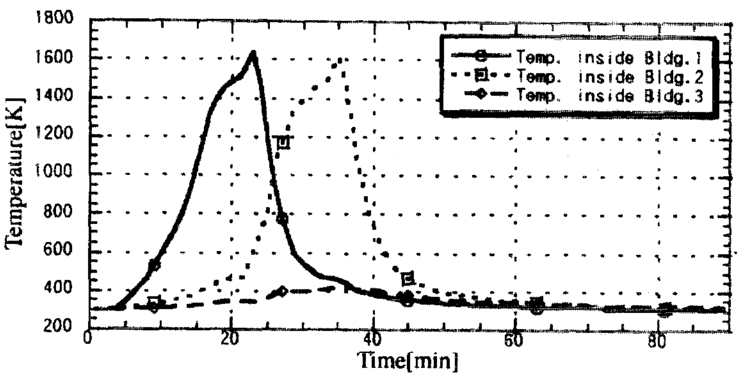


FIGURE 10. Temperature change-b (4.0m/s)

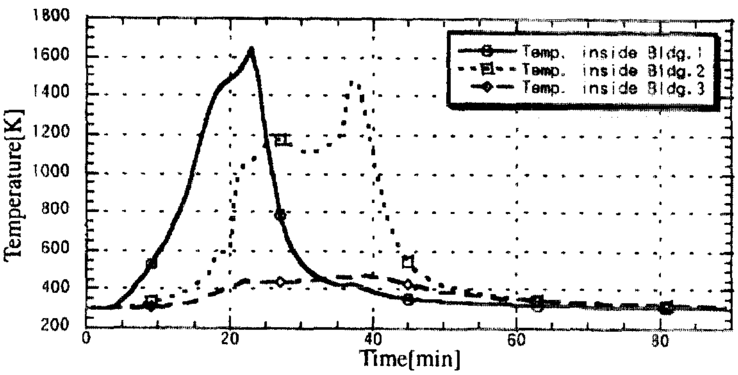


FIGURE 11. Temperature change-c (8.0m/s)

According to the calculation, the possibility of fire spread to the building of the lee side rose and the time for fire spread was shortened as the wind velocity get faster. That seems to be because the higher the wind velocity, the more the fire plume blown down so that the buildings were exposed to the higher temperature. The reason why the remotest buildings did not burn even if the wind velocity strengthens is that there was no direct radiation from the building of origin and the temperature due to fire plume did not rise to the critical ignition temperature of combustibles.

## 4. CONCLUDING REMARKS

The burning behavior of the fire spread model was examined for different wind velocities. The result shows that the wind velocity may become a factor affecting the spreading speed of fire.

Of course there is a lot to be done before a practically useful urban fire model can be obtained. The current model is nothing but the first step for such model.

## NOMENCLATURE

### Alphabets

| | |
|---|---|
| $A_D$ | area of doorway$[m^2]$ |
| $A_{floor}$ | area of floor$[m^2]$ |
| $A_{fuel}$ | surface area of the fuel$[m^2]$ |
| $A\sqrt{H}$ | opening factor$[m^{5/2}]$ |
| $A_w$ | area of wall$[m^2]$ |
| $b$ | half width of plume$[m]$ |
| $c$ | specific heat of wall$[kJ/kg \cdot K]$ |
| $C_N$ | wind pressure coefficient$[Pa/kJ]$ |
| $c_p$ | specific heat of gas$[kJ/kg \cdot K]$ |
| $E_f$ | emissive power of fire$[kW/m^2]$ |
| $E_j$ | emissive power of wall $-j[kW/m^2]$ |
| $F_{ij}$ | configuration factor from wall $-i$ to wall $-j$ |
| $g$ | acceleration of gravity$[kg/m^2]$ |
| $\boldsymbol{G_o}$ | positional vector of heat receiving building |
| $h_{fuel}$ | convection heat transfer coefficient of fuel$[lW/m^2K]$ |
| $h_i, h_o$ | convection heat transfer coefficient of wall$[kW/m^2]$ |
| $\Delta H_f, \Delta H_{O2}$ | heating value of combustibles and oxygen$[kJ/kg]$ |
| $k$ | heat transfer coefficient of wall$[kW/m \cdot K]$ |
| $\dot{m}_{b,i}$ | mass burning rate$[kg/s]$ |
| $\dot{m}_{io}, \dot{m}_{oi}$ | mass flow rate$[kg/s]$ |
| $\boldsymbol{P_O}$ | positional vector on plume axis |
| $\dot{q}''_0, \dot{q}''_l$ | incident heat flux to the wall per unit area$[kW/m^2]$ |
| $\dot{q}''_R$ | incident radiation flux per unit area$[kW/m^2]$ |
| $\dot{q}_v$ | heat absorption rate per unit wall volume$[kW/m^3]$ |
| $qL_f$ | heat of decomposition of combustibles$[kJ/kg]$ |
| $Q'$ | heat release rate per unit length$[kW/m^2]$ |
| $\dot{Q}_{c,i}$ | heat generation rate$[kW]$ |
| $\dot{Q}_D$ | heat loss rate through doorway$[kW/m^2]$ |
| $\dot{Q}_T$ | heat emission rate to outside$[kW]$ |
| $\dot{Q}_{w,i}, \dot{Q}_{w,o}$ | incident heat rate to the wall$[kW]$ |
| $s, t$ | width and height of the target wall$[m]$ |
| $T_f$ | decomposition temperature of fuel$[K]$ |
| $T_i, T_o$ | temperature inside and outside compartment$[K]$ |
| $T_{w,i}, T_{w,o}$ | wall surface temperature$[K]$ |
| $\Delta T_0$ | temperature rise above plume axis temperature$[K]$ |
| $\Delta T(r)$ | temperature rise above ambient temperature$[K]$ |
| $u$ | distance to the target$[m]$ |
| $U_\infty$ | wind velocity$[m/s]$ |
| $v_x, v_y$ | $x, y-$coodinate of wind direction$[m]$ |
| $V_i$ | volume of the compartment$[m^3]$ |
| $w$ | fire load density$[kg/m^2]$ |

| | |
|---|---|
| $Y_{f,i}, Y_{f,o}$ | *concentration of combustible gas* |
| $Y_{O2,i}, Y_{O2,o}$ | *concentration of oxygen* |

**Greeks**

| | |
|---|---|
| $\Gamma_{f,i}, \Gamma_{O2,i}$ | *consumption rate of fuel and oxygen*$[kg/s]$ |
| $\varepsilon_{w,i}, \varepsilon_{w,o}$ | *emissivity of wall* |
| $\eta$ | *angle between wind direction and normal vector*$[rad]$ |
| $\theta$ | *inclination of plume axis*$[rad]$ |
| $\Omega$ | *dimensionless wind velocity* |
| $\rho_i, \rho_o$ | *occupant gas density*$[kg/m^3]$ |
| $\phi$ | *fuel surface area coefficient*$[m^2/kg]$ |
| $\varphi_d, \varphi_w$ | *configuration factor of doorway and wall* |

(The case in which there is especially no notice on additional number, '*i*' stands for inside the compartment and '*o*' for outside.)

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